# Multilayer Mirrors: A New Horizon for Astronomical X-ray Optics

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An accidental discovery of X-rays in the year 1895 by Roentgen is one of the most influential contributions to the modern science and technology. These high energy electromagnetic waves quickly revolutionized many diversities of scientific research from bio-medical research to experimental quantum mechanics. Without any exception, X-ray astronomy is now a major area of interest in the field of Astronomy. Ever since the birth of X-ray astronomy in the year 1962, thousands of celestial bodies are being studied which are emitting X-rays with fascinating physics encrypted in it.

While the scientific importance of understanding the X-ray universe is justified beyond any debate, the practice of X-ray astronomy is challenged with major technological limitations. Unlike the X-ray sources we have in our laboratories, celestial objectsare often very faint and hence we need large area sensors to increase the efficiency of observation. But the major difficulty in building X-ray sensors lies in the development of mirrors which can efficiently reflect X-rays. As X-rays have small wavelengths, they pass through practically all substances with very little interaction. This makes building sensors and mirrors difficult for X-ray astronomy. This issue is traditionally addressed by using grazing incidence mirrors where X-rays reflect at a very small angle ($<0.5^{o}$) from the surface. Crudely, this is analogous to a stone bouncing off the surface of the water when it is put at some slant angle.

While grazing incidence X-ray optics is very popular in X-ray astronomy community, however it has many limitations. Telescopes made with these types of mirrors have a small band

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* Mr. Panini Singam, Ph.D. Scholar from Indian Institute of Astrophysics, Bengaluru, is pursuing his research on "Development of Multilayer Mirrors for Space based Astronomical Applications." His popular science story entitled "Multilayer Mirrors: A New Horizon for Astronomical X-Ray Optics" has been selected for AWSAR Award.

width, small effective area and are very bulky. Combined with the fact that X-rays from celestial objects don't enter earth's surface because of thick atmosphere, all X-ray telescopes have to be places in outer space. This technique is not only costly but lays severe limitations on size and weight of the instrument. To address this issue, we (in collaboration with IIA, ISRO, and RRCAT) have developed multilayer mirrors which can efficiently reflect X-rays even at very high angles. Multilayer mirrors, as name suggests, contain a series of thin atomic/ molecular layers of different materials on top of each other. When X-rays are incident at higher angles to the mirror, only small fraction rays are reflected while most of them just get transmitted. Since there are multiple layers of different materials on the top of each other, at each layer interface, the wave gets divided into transmitted and reflection components. Over a large number of layers, all the reflected component of X-rays at each layer gets added up to give an overall enhanced reflectivity from the mirror.

Typically all the mirrors we have fabricated consist of alternative metallic and non-metallic layers which are stacked to form a multilayer structure. We have fabricated Tungsten/ Boron Carbide (W/B4C) multilayers which contains a series of Tungsten layers alternating with Boron Carbide layer. The contrast in densities of Tungsten and Boron Carbide materials provide an excellent condition for maximizing overall reflectivity of the mirror. We have fabricated these mirrors at RRCAT, Indore by a technique known as magnetron sputtering. In this technique, a substrate (a smooth Silicon wafer on which multilayer structures are deposited) is exposed to vapours of different materials (Tungsten and Boron Carbide in our case) alternatively under controlled conditions. During each exposure of the substrate to these vapours, a thin layer of the order of a few nano-meters (nm) gets deposited on the substrate. This process is carefully repeated until a few hundreds of layers are deposited. An utmost care and optimization of coating conditions are required for multilayer structures with low interlayer roughness and minimal discontinuities in the layer.

We have fabricated a variety of multilayer mirrors by changing the thickness of each layer and with the different number of total layers. Multilayer mirrors show narrow band reflectivities at specific angles (Bragg peaks) at X-ray wavelength. As the thickness of each layer is varied, the angle at which these Bragg peaks occur varies. Physical properties like the surface roughness, stability, adhesion in the layers, and reflectivity varies significantly with the thickness of the layers. Hence, we have fabricated and studied their properties for multilayer mirrors with the thickness of layers varying from 0.8 nm to 3 nm. All these mirrors are tested at X-rays from energy 0.7 keV to 16 keV at Indus synchrotron radiation facility RRCAT to understand their behaviour. Multilayer mirrors with a wide range of thickness have their applications for specific requirements in astronomy. Small thickness multilayers have the reflectivity at high angles which are used for developing large effective area telescopes, while large thickness multilayers are observed to have higher reflection efficiencies. These results are reported in the Journal of Optics in 2017.

As we are developing these mirrors for space applications, it is very important to know their stability in the space environment. A major factor that can affect the performance of these mirrors is the rapid change in the ambient temperature of the telescope during satellite's orbit around the earth. Satellite in a typical low earth orbit experiences extreme temperatures from $-40^{o}$ C to $+50^{o}$

C over a span of 90 minutes. As these mirrors contain layers of contrasting materials, they may experience differential interlayer thermal expansion/ contraction over the orbiting period. This may increase the interlayer roughness and discontinuities among layers which will degrade the performance of mirror over time. To understand this effect, we have subjected our mirrors to the temperatures as experienced during the orbit of a satellite in regulated thermal chambers at ISITE-ISRO. We have studied multi-wavelength X-ray reflectivity of these mirrors before and after the thermal treatment. We have observed that the mirrors with small thickness layers are more stable and immune to the thermal treatment. We have reported these results in Journal of Astronomical Telescopes, Instruments and Systems, (JATIS), 2018.

One of the direct applications of these mirrors in astronomy is X-ray polarimetry. X-rays, like any other electromagnetic wave, have electric and magnetic fields perpendicularly oscillating normal to the wave propagation. The orientation of the electric field/ magnetic field gives the information about the polarization state of the light. In astronomy, polarization information of the light gives unique and important information about the properties of the celestial object. For example, X-ray polarimetric studies of an accreting black hole give precise information about the orientation, spin and mass of the black hole. Similarly, a variety of astrophysical sources like, Neutron stars, Magnetors, Pulsars, Active Galactic Nuclei (AGN), etc. are expected to produce polarized X-rays with fascinating physics behind it. But in X-ray regime, it is difficult to extract polarization information from the radiation. A mirror acts as a polarizing element when it reflects X-rays at $45^o$. But as discussed earlier, the reflection of X-ray s happens only at a very small angle ($< 0.5^o$). Since now we have technology and recipe to develop multilayer mirrors to have X-ray reflectivity at large angles, X-ray polarimetry is not far from reach. Towards this, we have developed a unique conceptual design of multilayer mirror based soft X-ray polarimetry which can operate less than 1 keV. There is no other technique currently available which can do the job without multilayer mirrors. We have published this design concept in a special edition on astronomical X-ray polarimetry by JATIS, 2018.

Our progress in understanding the behaviour of multilayer mirrors helps in developing next-generation astronomical X-ray instruments with enhanced capabilities to understand the mysteries of high energy events from the cosmic objects. Multilayer mirrors also contribute in opening a completely new window of observing the universe such as soft X-ray polarimetry. Capacity to fabricate a variety of good quality multilayer mirrors has reinvigorate new possibilities in the otherwise saturating field of astronomical X-ray optics.